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Possible Deviations from Simple Quark-Parton Models in High-Energy Antineutrino Differential Distributions*

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We have analyzed differential distributions for a sample of high-energy ν and $\bar{\nu}$ interactions. The antineutrino data require more antiquark component than expected from low-energy results. Also, some hints of energy-dependent effects have been observed in these distributions.

Charged-current neutrino (antineutrino) interactions $[\nu\ (\bar{\nu}) + N \to \mu^-\ (\mu^+) + \text{hadrons}]$ have long been recognized as providing fundamental information about nucleon structure. From a combination of deep-inelastic electron scattering experiments at Stanford Linear Accelerator Center[1] and studies of neutrino interactions at CERN[2] a rather simple description of this structure has emerged.

Basically, the low-energy data agree with an interpretation incorporating both a scaling hypothesis for the structure functions and the predictions of a simple quark-parton model. In this model, scattering dominantly occurs from pointlike, spin-$\frac{1}{2}$, fractionally charged constituents. Early studies of neutrino and antineutrino interactions at the higher energies of Fermilab have shown striking *qualitative* agreement with this same picture.[3]

The forms of the differential cross sections for an isoscalar target in this quark-parton model are given by

$$\frac{d^2\sigma^\nu}{dx\,dy} = \frac{G^2 M E_\nu}{4\pi}[q(x) + (1-y)^2\bar{q}(x)] \tag{1}$$

and

$$\frac{d^2\sigma^{\bar{\nu}}}{dx\,dy} = \frac{G^2 M E_{\bar{\nu}}}{4\pi}[\bar{q}(x) + (1-y)^2 q(x)], \tag{2}$$

where $x = Q^2/2ME_h$, $y = E_h/E_\nu$, M is the nucleon mass, and E_h is the energy transfer to hadrons in the laboratory system. The incident neutrino energy is $E_\nu = E_h + E_\mu$ and $Q^2 = 4E_\nu E_\mu \sin^2\theta/2$ is the square of the four-momentum transfer. Here E_μ and θ_μ are the laboratory final-state energy and scattering angle of the muon. The structure functions $q(x)$ and $\bar{q}(x)$ are related to the quark and antiquark momentum distributions in the nucleon. At low energies the antiquark component has been determined to be small and confined to small x.[2] This leads to the qualitative predictions that (1) $d\sigma^\nu/dy \sim$ flat and $d\sigma^{\bar{\nu}}/dy \sim (1-y)^2$, (2) the total cross sections σ_ν and $\sigma_{\bar{\nu}}$ grow linearly with energy, and (3) $\sigma^{\bar{\nu}}/\sigma^\nu \sim \frac{1}{3}$.

There are theoretical conjectures which would alter this picture. For example, the functions $q(x)$ and $\bar{q}(x)$ could have some Q^2 dependence, or there could be finite non-spin-$\frac{1}{2}$ contributions of the form $K(x, Q^2)(1-y)$. Energy-dependent effects could also arise from production (beyond some threshold) of new leptons or of hadrons composed of new quarks.

In this Letter we report on the observation of deviations from predictions of the simple quark-parton model. The data were taken with use of the California Institute of Technology–Fermilab apparatus and a narrow-band neutrino beam. The experiment was performed with short-spill (~1-msec) extraction from the accelerator (in order to do a neutral-current experiment simultaneously). The use of this short spill made it impossible to measure directly either the neutrino or antineutrino flux. This represents a serious limitation in the data sample since the absolute cross sections have not been measured and even the determination of the relative normal-

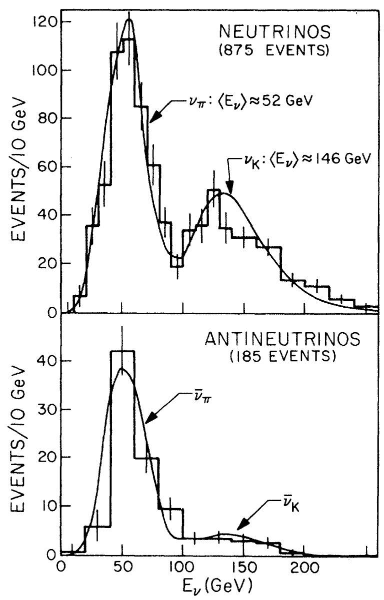

FIG. 1. Measured ν and $\bar\nu$ energy distributions for events traversing the muon spectrometer. The two-peak structure of the beam (broadened by our experimental resolutions) is apparent for neutrinos. For antineutrinos the lower $\bar\nu_k$ yield, reflecting the lower K^- yield, is evident.

ization of ν to $\bar\nu$ data requires further physical assumptions.

Our total sample of charged-current events within the fiducial volume consists of 1783 ν events and 307 $\bar\nu$ events. The muon traversed the toroidal muon spectrometer ($\theta_\mu \lesssim 100$ mrad) in 875 of the ν events and 185 of the $\bar\nu$ events. For these events θ_μ, E_μ, and E_h are measured, and therefore the neutrino total energy ($E_\nu = E_\mu + E_h$) and scaling variables are determined; for the remainder, only θ_μ and E_h were measured. In addition, it should be noted that approximately 10% of charged-current events produce a muon at such a large angle ($\theta_\mu \gtrsim 250$ mrad) or low energy ($E_\mu \lesssim 2.0$ GeV) that they cannot be distinguished from neutral-current events and therefore are not included in the analysis.

Figure 1 shows the distributions of total measured energy for neutrino and antineutrino events in which a final-state muon traversed the magnet. The characteristic two-peak spectrum from the dichromatic beam is apparent in the neutrino data. For antineutrinos, the relatively lower production of high-energy K^-'s is reflected by the smaller fraction of high-energy $\bar\nu$ events.

In order to test whether our data are consistent with the expectations of the quark-parton model, we have used the forms of Eqs. (1) and (2) and *assumed* a form for the structure functions, wherein the shape of $q(x) + \bar q(x) = F_2(x)$ is the same as $F_2^{ed}(x)$ and $\bar q(x) = \frac{1}{2}F_2(x)e^{-\lambda x}$.[4] In this parametrization, the value of λ determines the fraction of antiquark in the nucleon. We define this fraction as $\alpha = \bar Q/(Q+\bar Q)$, where $Q = \int_0^1 q(x)\,dx$, etc.

We have simultaneously fitted the y distributions for events with a muon traversing the magnet and the E_h distribution for events without a measured muon momentum (see Fig. 2). The fit to the antineutrino data requires a finite α (see Table I). The best value determined from a fit to all the data is $\alpha \approx 0.24^{+0.08}_{-0.13}$. The overall fit to the data is acceptable; however, the amount of antiquark is substantially larger than the usual expectations of a simple quark-parton model. In the context of this model, the ratio of total cross sections

$$\sigma_{\bar\nu}/\sigma_\nu = (2\alpha + 1)/(3 - 2\alpha).$$

For our best fit, the calculated value of this ratio is $\sigma_{\bar\nu}/\sigma_\nu \sim 0.6$. The simplest quark-parton model predicts, therefore, that this ratio would have

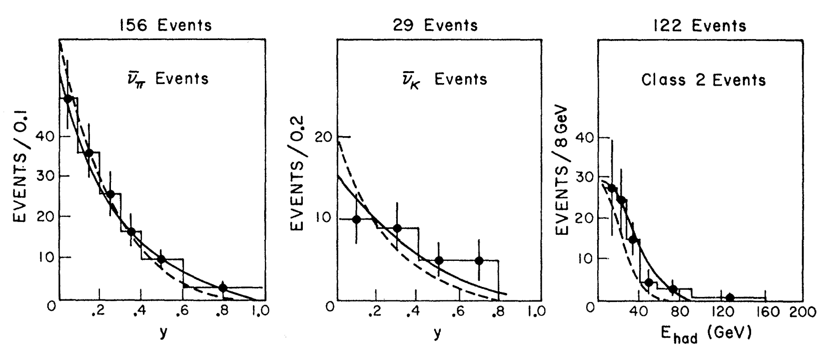

FIG. 2. Antineutrino charged-current distributions uncorrected for efficiency are shown. For comparison, fits for $\alpha = 0$ and $\alpha = 0.24$ are shown as dashed and solid curves, respectively.

TABLE I. Fits to the antineutrino distributions under different model assumptions.

Model	Free parameters	Calculated $\sigma_{\bar{\nu}}/\sigma_{\nu}$	$\bar{E}_{\bar{\nu}}$ (GeV)
Scaling	$\alpha = 0.24^{+0.08}_{-0.13}$	$0.59^{+0.10}_{-0.15}$	All E_{ν}
Nonscaling	$\alpha_{\pi} = 0.17^{+0.13}_{-0.11}$	$0.52^{+0.15}_{-0.11}$	50
	$\alpha_{K} = 0.32^{+0.18}_{-0.15}$	$0.69^{+0.31}_{-0.19}$	150
b-quark right-handed currents, $\alpha = 0.06$	$M_b = 5.1^{+0.9}_{-0.5}$	$0.44^{+0.03}_{-0.04}$	50
		$0.68^{+0.07}_{-0.09}$	150

grown significantly at the energies of this experiment (see Fig. 1) compared to low energies.[5]

These indications of energy-dependent effects have prompted us to analyze our data in two energy bins (π-decay antineutrinos, $E_{\bar{\nu}} < 90$ GeV, and K-decay antineutrinos, $E_{\bar{\nu}} > 90$ GeV) allowing a scale-breaking term. As can be seen in Table I, this analysis indicates an increasing value for α at higher energies. It is interesting to note that an increase in the fraction of antiquark with $E_{\bar{\nu}}$ is expected in asymptotically free field theories and leads to a growing $\sigma_{\bar{\nu}}/\sigma_{\nu}$ ratio.[6]

It should also be noted, however, that our data are consistent with other explanations such as production of b quarks with right-handed currents.[7] To compare with such a model, we have fixed the amount of antiquark at the low-energy value[2] ($\alpha \sim 0.06$) and have varied the mass of the b quark, which is the only free parameter. As shown in Table I, a good fit can be obtained with inclusion of a b quark having mass $M_b \sim 5.1$ GeV/c^2. This model for the charged currents would also imply a growing $\sigma_{\bar{\nu}}/\sigma_{\nu}$ ratio above the b-quark threshold.

It is not possible with this data to distinguish such diverse explanations or possibly others which could affect antineutrino distributions. All that can be inferred with any certainty from our data is that the antineutrino y distributions have apparently changed character and are flatter at high energies.[8] It is not even valid, without further assumptions, to conclude that the data necessarily requires a growing $\sigma_{\bar{\nu}}/\sigma_{\nu}$ ratio. All comparisons between neutrino and antineutrino in this data have in common an assumption that charge symmetry is valid as $y \to 0$ [i.e., $(d\sigma^{\nu}/dy)_{y=0} = (d\sigma^{\bar{\nu}}/dy)_{y=0}$]. This would be approximately true in the theories mentioned above. Since these data are

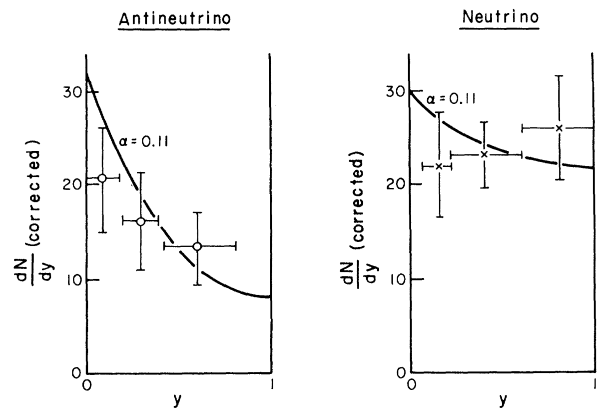

FIG. 3. Test of charge symmetry at small y. ν and $\bar{\nu}$ data have been normalized at $y=0$ for $x>0.1$. The distributions for $x<0.1$ (corrected for efficiency) are shown. For comparison, expected distributions for 11% antiquark component are also indicated. Whether charge symmetry at small y or W holds well enough to normalize ν and $\bar{\nu}$ data "internally" is unclear.

not independently normalized, however, we cannot check this hypothesis directly.

Charge symmetry has been tested in ν and $\bar{\nu}$ data and violations have been reported[9] which shed some doubt on the reliability of normalizing ν to $\bar{\nu}$ data at small y. We have studied our data for such anomalous effects. The procedure was to divide the data into two bins, $x > 0.1$ and $x < 0.1$. The large-x data behave as expected, with $d\sigma^{\nu}/dy \sim$ flat and $d\sigma^{\bar{\nu}}/dy \sim (1-y)^2$. Charge symmetry is then assumed to hold in this region and the data with $x > 0.1$ for ν and $\bar{\nu}$ were normalized to each other at $y = 0$. With use of this relative normalization, the data with $x < 0.1$ for ν and $\bar{\nu}$ were then compared.

The results of this analysis for mean observed energy of 50 GeV are shown in Fig. 3. Although the statistics are limited, our data show no obvious violation of charge symmetry at small y and $x < 0.1$. However, we have not performed at this time a test decisive enough to determine whether *any* scheme for normalizing internally to distributions is valid at the level necessary to infer the behavior of the $\bar{\nu}$ to ν total-cross-section ratio.[10] Therefore, we emphasize that our data show strong indications that the antineutrino distributions have changed shape and become flatter at high energies.[11] However, to determine unambiguously whether this observation represents an *excess* of antineutrino events at large y, a *redistribution* of events in y, or, indeed, a *lack* of antineutrino events at small y, will require good-statistics distributions normalized to independently measured incident flux. Since we have recently taken such data, results should be forthcoming soon.

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[3]B. C. Barish *et al.*, Phys. Rev. Lett. 31, 656 (1973); A. Benvenuti *et al.*, Phys. Rev. Lett. 30, 1084 (1973).

[4]This paper mainly concerns itself with antineutrino y distributions. We have varied the assumed forms of the x distributions and demonstrated that our conclusions are rather insensitive to the actual form.

[5]Evidence for a rising $\sigma_{\bar{\nu}}/\sigma_\nu$ ratio with E_ν has recently been reported by A. Benvenuti *et al.*, Phys. Rev. Lett. 37, 189 (1976).

[6]The magnitude of asymptotic-freedom corrections has been addressed by G. Altarelli *et al.*, Phys. Lett. 63B, 183 (1976), and R. Michael Barnett *et al.*, Phys. Rev. Lett. 37, 1313 (1976).

[7]R. Michael Barnett, Phys. Rev. Lett. 36, 1163 (1976).

[8]Similar effects have been reported by A. Benvenuti *et al.*, Phys. Rev. Lett. 36, 1478 (1976), and references therein.

[9]B. Aubert *et al.*, Phys. Rev. Lett. 33, 984 (1974), and D. Cline, in Proceedings of the International Conference on High Energy Physics, Palermo, Italy, June 1975 (unpublished).

[10]We have previously reported total ν and $\bar{\nu}$ cross sections based on a small sample of data normalized to the ν and $\bar{\nu}$ flux. This measurement (based on eleven $\bar{\nu}$ events at $E_{\bar{\nu}} = 108$ GeV) showed no indication of a rising $\sigma_{\bar{\nu}}/\sigma_\nu$ ratio. See B. C. Barish *et al.*, Phys. Rev. Lett. 35, 1316 (1975).

[11]It should be noted that the hadron energy, E_h, is measured by using calorimetry techniques and calibrated with charged hadrons of known energy. If the final hadronic state in neutrino collisions contained a substantially larger fraction of its energy in π^0's than the interaction of charged hadrons of the same energy, the calorimetry calibration would be systematically different by up to 20%. See e.g., F. J. Sciulli, in Proceedings of the Calorimetry Workshop, Fermi National Accelerator Laboratory, May 1975 (unpublished), p. 79.

Molecular Charmonium: A New Spectroscopy?*

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Recent data compel us to interpret several peaks in the cross section of e^-e^+ annihilation into hadrons as being due to the production of four-quark molecules, i.e., resonances between two charmed mesons. A rich spectroscopy of such states is predicted and may be studied in e^-e^+ annihilation.

Properties of recently discovered charmed particles,[1] D^0, D^+, D^{*0}, and D^{*+}, are in good agreement with a simple picture of hadrons as bound states of quarks in a color gauge theory.[2] The model of mesons as quark-antiquark bound states (and baryons as three-quark bound states) with long-range spin-independent binding and short-range spin-dependent color gluon exchange adequately describes many features of normal hadron spectroscopy.[2,3] Moreover, it has correctly predicted the qualitative behavior of the charmonium states and of charmed hadrons themselves.[2] This Letter is focused on one remaining striking and generally unexpected feature of charmed-meson production in e^-e^+ annihilation. Much data in which D mesons are seen are taken at a peak in the annihilation cross section, at $\sqrt{s} = 4.028$ GeV, where the yield of charmed mesons was expected to be, and indeed is, high. Analysis of the recoil-mass spectrum against detected D^0's indicates that $\sigma(\bar{D}^0D^0)$, $\sigma(\bar{D}^0D^{*0}+\bar{D}^{*0}D^0)$, and $\sigma(\bar{D}^{*0}D^{*0})$ are in the ratios 1: ~8: ~11 at this energy.[4,5] Estimates of charmed-meson masses reveal that the available decay energies are ~300, ~160, and ~18 MeV, respectively. It is remarkable that the $\bar{D}^{*0}D^{*0}$ mode, with so little phase